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The grant included two renewals/extensions of the original Young Investigator Program Award.

14. ABSTRACT
The principal goals of Phases I & II (the YIP Award and Supplement) were to:
1. Enhance the performance capability of streamlined AUVs by extending their operating range to include hover.
2. Develop energy-based nonlinear control design tools and demonstrate them in practical vehicle applications.
3. Develop algorithms for simple flow-field modeling and identification using data from a platoon of small AUVs.

The principal goal of Phase III was to:
4. Address the lateral/directional control challenges associated with low-speed, high angle of attack flight of underwater gliders, particularly the XRay/Liberdade blended wing-body glider developed jointly by Scripps Institute of Oceanography and the University of Washington Applied Physics Lab.

15. SUBJECT TERMS
feedback control, energy shaping, internal actuators, underwater gliders

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Phase I	**YIP Award: Low velocity attitude control for underwater vehicles using internal actuators**
Phase II	**YIP Supplement: Real-time flow-field estimation for cooperative autonomous underwater vehicle mission planning**
Phase III	**Internally actuated lateral-directional maneuvering for a blended wing-body underwater glider**

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PHASE I & II LONG-TERM GOALS

The role of autonomous underwater vehicles (AUVs) in the U. S. Navy continues to expand. As tasks become more demanding, AUVs are expected perform over a broader range of operating conditions. Stand-off applications, such as mine reconnaissance, require streamlined vehicles which can quickly and efficiently travel moderate distances. Docking, manipulation, and many sensing tasks, on the other hand, may require a hovering capability that conventional streamlined vehicles lack.

This project explored the use of internal actuators, including internal rotors and servo-actuated masses, to control AUVs, particularly streamlined AUVs moving at low speed. The conventional way to control an AUV at low speed is to use multiple thrusters. Additional thrusters, however, cause more drag at higher speeds and are subject to fouling and corrosion. Internal actuators are an efficient and reliable alternative. The inherent robustness of moving mass actuators, for example, and their effectiveness at low speeds has led to their use as attitude control actuators for an array of buoyancy driven underwater gliders.

While the operating envelope of streamlined AUVs may be expanded by introducing new actuation concepts, it may also be expanded through novel control design techniques which respect and exploit a vehicle's natural, nonlinear dynamics. Energy-based control design can provide controllers which are energy efficient, because they respect the essential physics, are robust to model uncertainty, and perform well over a large portion of the dynamic phase space. The idea of controlling a mechanical system by using feedback to reshape its total energy and its dynamic structure is a notion that finds natural application for internally actuated vehicles. These vehicles are underactuated, nonlinear control systems, a class of systems to which the most common nonlinear control techniques do not apply.

The principal long-term goals of the Phase I research project were to:

1. Enhance the performance capability of streamlined AUVs by extending their operating range to include hover.
2. Develop energy-based nonlinear control design tools and demonstrate them in practical vehicle applications.

Under a supplemental research agreement, a third goal was added:

3. Develop algorithms for simple flow-field modeling and identification using data from a platoon of small AUVs.

This third goal, enabled by a supplement to the original YIP grant, supported real-time mission planning and re-planning for AUV platoons performing environmental assessment. The algorithms developed under this effort were implemented in a collaborative experiment with Naval Surface Warfare Center-Panama City (NSWC-PC) and Prof. D. Stilwell of Virginia Tech.

PHASE I & II OBJECTIVES

The three major objectives supporting the first two long-term goals (Phase I) included:

1. Develop provably effective low-velocity control strategies for a streamlined AUV with internal rotor actuators or servo-actuated internal masses.
2. Evaluate these strategies with regard to practical issues not explicitly considered in the control design process, and modify the control strategies as necessary.
3. Demonstrate feasible control strategies experimentally using laboratory-scale experimental AUVs.

The primary objective supporting the third long-term goal (Phase II) was to:

4. Develop low-dimensional flow models whose parameters can be identified in real-time using a platoon of AUVs and implement these algorithms, in collaboration Dr. D. Stilwell and Navy scientists and engineers, in an environmental assessment experiment.

PHASE I & II APPROACH

With regard to low-velocity control of streamlined AUVs, the approach is divided into three major tasks: modeling, control design, and validation. The first task involves developing vehicle models which are sufficiently rich to capture important nonlinear dynamics but sufficiently simple to be amenable to control design. The second task involves extending new, energy-based nonlinear control methods for application to AUVs. The third task involves evaluating proposed control strategies through simulation and using AUVs developed at Virginia Tech.

The challenge in modeling for control design is to develop a model which captures as much of the physics as possible while admitting a tractable control design problem. Vehicle modeling efforts have

focused on developing reduced-dimensional Hamiltonian models for internally actuated AUVs. These models take the general form

$$\dot{z} = \Lambda(z)\nabla H(z) + G(z)u$$

where z is the system state vector, u is the input vector, Λ is a skew-symmetric matrix that defines the dynamic structure, G is an input matrix, and H is the Hamiltonian function that expresses the system energy. While these models are based on potential flow theory, they capture important nonlinear fluid effects. Nonconservative effects, such as viscous forces and propulsion, are appended as generalized forces Q:

$$\dot{z} = \Lambda(z)\nabla H(z) + G(z)u + Q$$

Hamiltonian control systems can be controlled by defining feedback that preserves the Hamiltonian (energy-conserving) nature of the system but which shapes the energy and the dynamic structure. In terms of the general system model above, the problem is to determine a feedback control law $u(z)$ such that the closed-loop system takes the form

$$\dot{z} = \Lambda_c(z)\nabla H_c(z) + Q_c$$

where the dynamic structure matrix Λ and the Hamiltonian H are modified in the closed-loop system to obtain the desired performance. The generalized forces Q are also modified by the control law; for a well-designed control law, these forces enhance the system performance. This technique has been applied to the problem of stabilizing translation of a streamlined AUV with internal rotor actuators [Woolsey & Leonard, 2002] and underwater and space vehicles with moving mass actuators [Woolsey, 2005; Reddy & Woolsey, 2005; Reddy, 2005].

Figure 1. Internally Actuated, Modular Bodied, Untethered Submersible (IAMBUS)

AUV control strategies developed using energy-based techniques may be validated numerically and through experiments. Numerical modeling provides a first look at unmodeled effects due to model uncertainty, sensor noise, and actuator saturation. Numerical and analytical parametric studies provide guidelines for the feasible design and use of internal actuators. An experimental platform developed under this project, the Internally Actuated, Modular Bodied, Untethered Submersible (IAMBUS), was used to test the effectiveness of internal rotor actuators for low-speed AUV control; see Figure 1. The base body of the vehicle is a seventeen inch spherical pressure housing which contains power, computation, sensing, and an internal actuator module. The internal actuators are an assembly of three,

orthogonal internal rotors. Besides providing a proof of concept and a test-bed for internal control of AUVs, IAMBUS serves as a realistic spacecraft attitude simulator with full rotational freedom. The experimental effort involving IAMBUS focuses on attitude stabilization and tracking using reaction wheels operated according to energy-based nonlinear control laws.

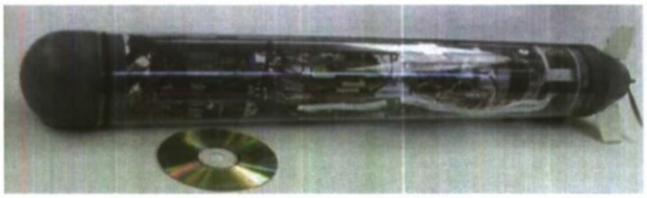

Figure 2. Prof. D. Stilwell's Virginia Tech Miniature AUV (VTMAUV).
[A 3.75 inch diameter, cylindrical-hulled AUV with a single rear thruster and three servo-actuated tail fins.]

While IAMBUS provides an ideal platform for experiments involving attitude control in hover, control of a streamlined AUV moving at low speed was more easily demonstrated in coordination with Dr. Daniel Stilwell, another ONR Young Investigator at Virginia Tech. Dr. Stilwell's research group has developed a miniature AUV, shown in Figure 2. A moving mass actuator module, shown in Figure 3, was added to provide a pitch control moment whose effectiveness is independent of vehicle speed. Because the miniature AUV is slightly buoyant, it must travel at a negative pitch angle to maintain depth. A moving mass actuator allows the vehicle to generate the necessary control moment while maintaining the stern planes at zero deflection, which maximizes their useful range for disturbance rejection. Analysis detailed in [Nickell, 2005] includes an investigation of the effectiveness of supplemental wings to increase efficiency and further lower the operational speed.

Figure 3. A moving mass actuator module for use with the VTMAUV.
[A 1.75 inch diameter, cylindrical pressure housing containing a movable mass driven by a servo-actuated lead screw.]

A supplemental effort involved developing low-dimensional flow field models whose parameters can be identified in real-time using a platoon of AUVs. Such models would improve navigational performance of minimally instrumented AUVs such as the VTMAUV. A secondary objective of this effort was to establish and strengthen research ties between the PI and Navy scientists and engineers through an environmental assessment experiment performed at NSWC-PC.

The approach to flow field estimation is to assume a flow field model of the form

$$V(r) = U + A(r - r_s)w(\|r - r_s\|)$$

which includes a uniform flow component U and a component due to a single flow singularity located at r_S. The magnitude of the singularity-induced flow is bounded by the "weakening function" w. The unknown model parameters are identified using navigational errors obtained when vehicles in the platoon surface to obtain new GPS position measurements.

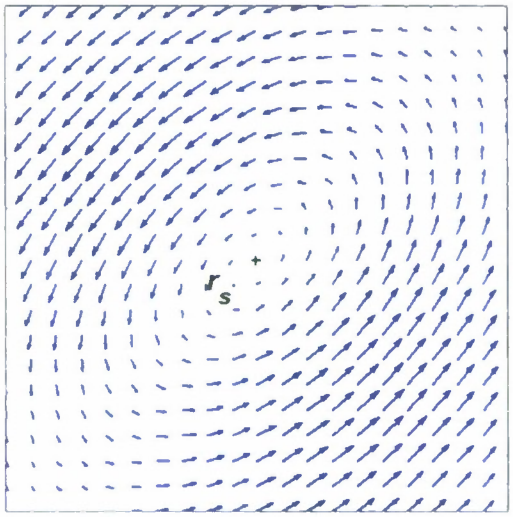

Figure 4. Example of a flow singularity.

Participants, in addition to the PI, who were sponsored directly by this grant include

- Dr. Hye-Young Kim, as a postdoctoral research assistant,
- Nate Lambeth, as an undergraduate research assistant in ocean engineering,
- Mike Morrow, as a Master's student in aerospace engineering,
- Chris Nickell, as an undergraduate and Master's student in aerospace engineering,
- Jan Petrich, as a PhD student in electrical engineering (supported half-time).
- Dr. Konda Reddy, as a PhD student in engineering science and mechanics,
- Chris Schultz, as a Master's student in aerospace engineering.

Other collaborators who were not sponsored by this grant include

- Dr. Dan Stilwell, an assistant professor in electrical engineering,
- Dr. Jan Crane, a researcher with NSWC-PC, and
- Laszlo Techy, as a PhD student in aerospace engineering.

PHASE I & II WORK COMPLETED

Completed work is presented in terms of the three major tasks: modeling, control design, and validation. In the area of modeling, we developed reduced-dimensional Hamiltonian control system models for underwater vehicles with moving mass actuators [Woolsey, 2005]. These models include an unconstrained (three degree of freedom) point mass and a point mass which is constrained to move along a linear track. These models have been used to develop control laws for AUVs with moving mass actuators, including conventionally propelled, streamlined AUVs [Nickell, Woolsey, & Stilwell,

2005; Nickell, 2005] and buoyancy-driven underwater gliders [Morrow, Woolsey, & Hagerman, 2005; Morrow, 2005].

In the combined areas of modeling and control design, Kim & Woolsey [2004, 2007] introduced a global, quasi-steady model of the viscous force acting on a spheroidal vehicle in order to capture the gross effect of lift and drag over the entire range of vehicle motion. Using this model, and an energy-based nonlinear control technique called feedback passivation, we developed a control law which globally asymptotically stabilizes streamlined translation of a conventional AUV in any desired inertial direction. More recently Woolsey [2006] and Woolsey and Techy [2009] modified the approach and used potential shaping to achieve almost global directional stabilization and cross-track control. Because the approach uses an extremely general hydrodynamic model, the results are robust to uncertainty in the viscous force and moment; these effects are notoriously difficult to model accurately.

In terms of general control methodology, we modified a nonlinear control technique applicable to underactuated mechanical systems (including AUVs with internal actuators) to expand the class of eligible systems and to provide greater freedom for tuning controller performance [Woolsey, Reddy, Bloch, Chang, Leonard, & Marsden, 2004]. The technique, known as the method of controlled Lagrangians, involves shaping a system's kinetic and potential energy through feedback. The extension introduced energy-conserving artificial gyroscopic forces in the closed-loop system. Introducing gyroscopic forces in a Lagrangian system is equivalent to modifying the Hamiltonian dynamic structure matrix Λ mentioned in the previous section. As part of this work, we also characterized the important effect of physical damping in energy-shaping control methods. (An understanding of nonconservative effects is crucial if one is to use this technique for marine vehicle control.) As a simple example, we applied the technique to asymptotically stabilize a pendulum on a cart. We proved that the region of attraction contains all states for which the pendulum is elevated above horizontal, demonstrating the large performance envelopes one can obtain using nonlinear control. The control law was implemented in an experiment, as described in Reddy, Whitacre, & Woolsey [2004]. Experimental results showed that the addition of a switching controller could improve local performance in the face of model uncertainty, while retaining the large performance envelope. More recently, we have applied kinetic shaping to the problem of controlling an AUV with a moving mass actuator [Reddy & Woolsey, 2005; Reddy, 2005].

To partially validate our vehicle models and control techniques, we constructed IAMBUS, shown in Figure 1. The base module of IAMBUS comprises a spherical pressure housing, an on-board computer, a ballast actuator, assorted sensors and three internal rotor actuators [Schultz & Woolsey, 2003]. IAMBUS provides a unique platform for testing attitude control schemes for AUVs moving at low speed. Using IAMBUS as a spacecraft attitude simulator with full rotational freedom, we demonstrated the effective use of potential energy-shaping feedback for nonlinear attitude stabilization. The results were presented in an undergraduate student research paper by William Whitacre at the AIAA Midatlantic Regional Student Conference [Whitacre, 2004]. (The paper won first prize and was invited for presentation at two other AIAA-sponsored technical conferences.)

Control of a streamlined AUV moving at low speed can also be accomplished using a moving mass actuator (MMA). We analyzed the utility of a MMA, used in concert with an optional, supplemental wing, to enable control of buoyant or heavy, streamlined AUVs at very low speeds. To illustrate the results, we developed a modular MMA for use on Dr. Dan Stilwell's VTMAUV. The assembly was

tested in Panama City, FL, as part of joint experiments with NSWC-PC personnel in June 2005. The results are described in detail in [Nickell, Woolsey, & Stilwell, 2005; Nickell, 2005].

PHASE I & II RESULTS

In the area of modeling, we developed reduced-dimensional Hamiltonian control system models for an AUV with a moving mass actuator. The Hamiltonian properties, which had not previously been recognized, are of value in developing energy-based control laws for vehicles with moving mass actuators, such as buoyancy driven underwater gliders. In a related project, for example, we used one of these models to demonstrate the potential utility of buoyancy driven gliders for exploring the terrain of Titan, the largest moon of Saturn. These Hamiltonian dynamic models are also of value in studying robustness to unmodeled dynamics, such as fuel slosh or vibrational modes. For example, one of these models led to the first formal proof of stability for major axis rotation of a rigid body with a point mass oscillating parallel to the spin axis, a result which is relevant for spacecraft with nutation dampers.

In the areas of control design and validation, we modified the method of controlled Lagrangians to broaden the class of eligible systems and to give greater freedom in tuning performance. The modification introduced additional energy-conserving forces in the closed-loop system. We also characterized the effect of dissipative forces, such as hydrodynamic drag, on systems controlled using this technique.

We developed a potential-shaping attitude control law for an AUV in hover using internal rotor actuators. The control law provides semi-global asymptotic attitude stability. It was demonstrated using IAMBUS, an internal rotor-actuated AUV developed at Virginia Tech.

Figure 5. IAMBUS in operation.

Another important result, published more recently, was the development of a globally asymptotically stabilizing attitude control law for conventional streamlined AUVs in forward flight. The control law drives the vehicle from any initial state to constant-speed translation in any desired final direction. A simple extension provides a line-following control law which, simulations suggest, globally asymptotically stabilizes motion along a desired linear path.

We developed preliminary design guidelines for streamlined AUVs with a fixed wing and thruster and moving mass actuators. Specifically, we developed criteria to determine whether it is more or less efficient to include a wing for low-speed flight of a buoyant or heavy AUV. The need for such design guidance was alluded to in [Davis, Eriksen, and Jones, 2002]. We have demonstrated this capability in sea trials using a moving mass actuator module together with Dr. D. Stilwell's VTMAUV.

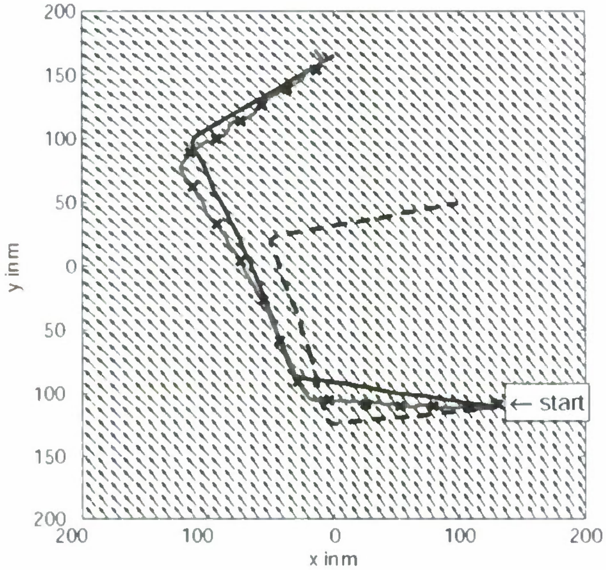

Figure 6. Actual (solid gray), dead-reckoned (dashed black), and flow-field-corrected (solid black) trajectories for an AUV travelling in a planar flow field. (Data taken at Hog Island Bay, VA.)

In a supplemental effort focused on flow field estimation, we have developed a technique for identifying a simple planar flow model from navigational errors in a platoon of AUVs. In an example application in Hog Island Bay, Virginia, the technique reduced the navigational error of a given AUV from 34 percent of distance travelled (%DT) to just under 6%DT.

PHASE I & II IMPACT/APPLICATIONS

Internally actuated AUVs are capable of operating at low speeds where fin actuators are ineffective and they can perform extended duty sampling tasks, because of improved robustness and efficiency. These vehicles resist or tolerate fouling, corrosion, and other damage. The vehicle hull has greater integrity because actuator power and control signals need not pass through it. Design guidelines developed through this effort inform potential users of the trade-offs involved in sizing internal actuators for a given application.

The energy-based control design methods developed for internally actuated AUVs enable these vehicles to operate at low speeds in dynamic and uncertain environments. These techniques are also useful for other vehicle applications, including unmanned surface vessels, atmospheric gliders and lighter-than-air vehicles, and orbiting or re-entering spacecraft.

The flow field estimation technique developed as a supplemental effort is simple to implement and effective at improving vehicle navigation for vehicles that are incapable of measuring relative flow. The approach will allow improved coordination of multiple AUVs navigating in a dynamic environment.

PHASE III LONG-TERM GOALS

The emergence and success of underwater gliders as long-term, mobile ocean sampling assets suggests alternate uses for persistent and stealthy maritime surveillance and reconnaissance. A recent ONR-commissioned performance comparison of existing "legacy gliders" underscored this observation, but also suggested a major change in design philosophy [Jenkins et al, 2003]. Each of the legacy gliders has a very small buoyancy lung and features a body-of-revolution hull with distinct, fixed wings [Eriksen et al, 2001; Sherman et al, 2001; Webb et al, 2001]. In order to obtain depth profiles of oceanographic properties, these vehicles were designed to perform relatively steep ascents and descents. The use of buoyancy-driven gliders for persistent and stealthy maritime reconnaissance, however, requires more efficient vehicle design and operation. According to the analysis reported in [Jenkins et al, 2003], greater efficiency dictates

- a blended, wing-body hull form, to increase the wing area,
- a large buoyant lung capacity, to increase wing loading, and
- operation at or near maximum lift-to-drag.

Underwater glider physics is well understood and the potential benefits of a wing-body hull-form are clearly worth exploiting. Precise control of lateral-directional (turning) motions using only buoyancy ballonets and moving masses is challenging, though. Including a conventional rudder is one way of ensuring precise directional control; indeed, one of the legacy gliders (the battery-operated *Slocum* glider) does use a conventional rudder. The goal of developing an autonomous underwater vehicle (AUV) for *persistent* maritime reconnaissance is better served, however, by using internal actuators that are protected from fouling and corrosion and other damage. This project focuses on the lateral-directional control challenges associated with low-speed, high angle of attack flight of an internally actuated, blended wing-body underwater glider. The technology development effort that is already under way at the Scripps Institute of Oceanography's Marine Physical Laboratory (SIO/MPL) and the University of Washington's Applied Physics Laboratory (UW/APL) will benefit from this parallel effort in model-based control design and analysis.

PHASE III OBJECTIVES

The principal aim of this project was to develop and validate model-based steering control laws for the blended wing-body glider being developed by SIO and UW/APL. The specific objectives supporting this goal are:

- Assemble a full and accurate dynamic model of the prototype blended wing-body underwater glider.
- Implement the model in a Matlab/Simulink simulation.
- Develop and validate effective steering control laws for the prototype vehicle and demonstrate them in simulation.
- Develop and validate reorientation and steering control laws for advanced maneuvers, such as the "knife-edge" maneuver.
- If practical, implement resulting control laws on the vehicle prototype and tune their performance.

Particular emphasis was given to analytical approaches, as illustrated in [Graver, Liu, Woolsey, & Leonard, 1996], which may not only improve performance of the blended wing-body glider but may also provide more general insight into glider stability and maneuverability and provide guidelines for future designs.

PHASE III APPROACH

To characterize steady turning motions for underwater gliders, we begin by considering wings level equilibrium flight and consider turning motion as a perturbation. Given a desired equilibrium speed and glide path angle, one may determine the center of gravity (CG) location and the net weight required. The resulting longitudinal gliding equilibrium is the nominal solution to a regular perturbation problem in which the vehicle turn rate is the perturbation parameter.

The derivation of analytical conditions for steady turning motions requires a vehicle dynamic model. Fairly complete models for the dynamics of underwater gliders, including hydrodynamic forces, buoyancy and added mass effects, and the nonlinear coupling between glider and moving internal masses are described in [Graver, 2005] and [Leonard & Graver, 2001]. An extension of these models is the basis for this investigation of stability and controllability of open- and closed-loop longitudinal gliding flight. Although steady turning motions are illustrated in [Graver, 2005] and [Bhatta, 2006], these were obtained numerically for a vehicle with specific parameter values, so little insight can be gained about the relationship between parameter values and the turning motion characteristics. A preferable approach is to retain a purely analytical model, as in [Graver, Liu, Woolsey, & Leonard, 1996] for the longitudinal case, and to study existence and stability of steady turning motions for general parameter values.

Having obtained approximate analytical solutions for steady turning motions for a general underwater glider model, we will investigate motion planning strategies in terms of feasibility and optimality. The simplest approach involves switching between steady wings level flight, in descent or ascent, and steady turning motions as required by the desired maneuver. Several questions arise, though:

- Is this strategy feasible, given that the solutions for steady turning motions are only approximate?
- If closed-loop control is used to maintain a desired turn rate, in the face of model and approximation uncertainty, what effect will this have on energy usage?
- Is this strategy energy-optimal, either for the quasi-steady system or under the full dynamics?
- If the strategy is not energy-optimal, how does it compare to true energy-optimal maneuvers?

The answers to these questions inform the motion planning and control problem for underwater gliders, leading to efficient behaviors that preserve the exceptional energy efficiency of these vehicles.

Participants, in addition to the PI, who were sponsored directly by this grant for the Phase III effort include

- Nina Mahmoudian, as a PhD student in aerospace engineering

Other collaborators who were not sponsored by this grant include

- Lt. Col. Robert Kraus (USAF), a PhD student in aerospace engineering,
- Dr. Jim Luby, University of Washington/Applied Physics Lab, and
- Dr. Eugene Cliff, Reynolds Metals Professor Emeritus of aerospace and ocean engineering,

PHASE III WORK COMPLETED

Starting from the longitudinal equilibrium analysis presented in [Graver, Liu, Woolsey, & Leonard, 1996], we have introduced a structured perturbation leading to steady, turning flight. The perturbation parameter ε is the (nondimensional) turn rate. Paths corresponding to unperturbed and perturbed motions are shown in Figure 7.

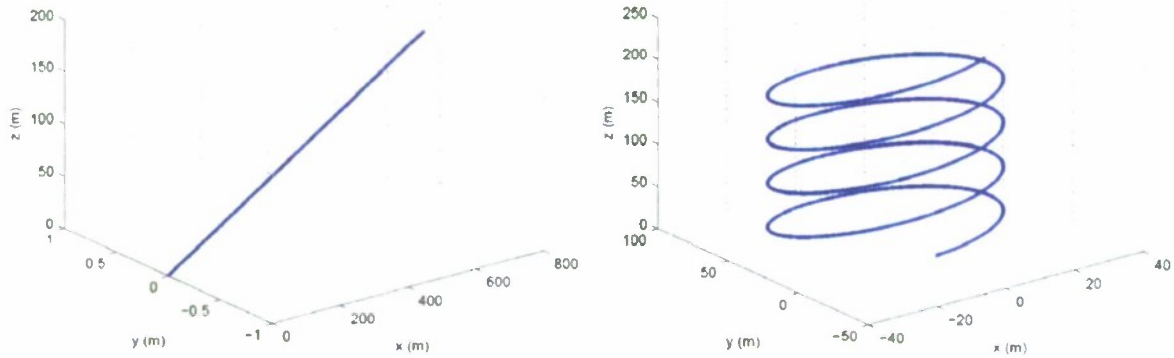

Figure 7. Linear path (left) followed by an underwater glider in wings level, equilibrium flight ($\varepsilon = 0$) and helical path (right) followed during steady, turning flight ($\varepsilon = 0.01$). The vehicle parameters are those described in [Bhatta, 2006] for the Slocum glider.

An interesting feature of the approximate solution is that, to first order in turn rate, the speed, angle of attack, and net weight remain constant. The primary (first order) contributors to steady turning motion are lateral mass deflections and rudder deflections (if a rudder is present) and these deflections have no first order effect on speed or angle of attack. In practice, it is considerably more costly to change the vehicle's net weight than to, say, shift the center of gravity laterally. The problem of controlling longitudinal motion (speed and glide path angle) decouples from the problem of controlling directional motion, to first order in turn rate. This observation suggests an energy efficient approach to motion planning based on results for nonholonomic mobile robots.

In parallel with the steady motion analysis, an M.S. candidate in ocean engineering used the popular USAERO commercial unsteady hydrodynamics software to develop a hydrodynamic model for the blended wing-body glider designed by SIO/MPL and UW/APL. Key hydrodynamic derivatives being investigated include the added mass and inertia and hydrodynamic inertial coupling – these terms require either experimentation or an unsteady computational fluid dynamics (CFD) package such as USAERO. The results of this CFD analysis for the blended wing-body glider allow the application of the analytical results for turning equilibria to that specific example. In addition determining the inviscid (added mass/inertia) parameters for the *XRay/Liberdade*, the student used USAERO to determine similar paramaters for *Slocum*. He also used common semi-empirical tools to determine the viscous parameters (stability derivatives) for *Slocum*. The results are detailed in [Geisbert, 2007].

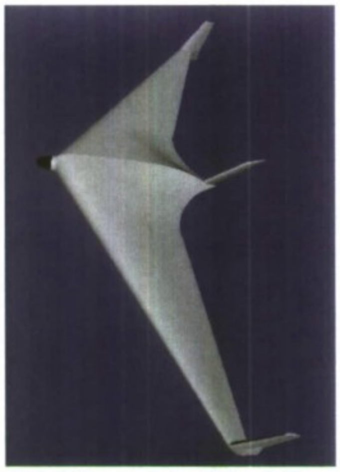

Figure 8. SIO/MPL and UW/APL 3D model of the* Liberdade/XRay *underwater glider, imported into the UMBRA modeling and simulation environment.

To aid visualization of the results, the blended wing-body glider model provided by SIO/MPL and UW/APL was ported into the UMBRA[1] modeling and simulation environment developed by researchers at Sandia National Laboratory; see Figure 8. Position and orientation data from simulations or experiments may be imported into UMBRA and re-animated using the 3D vehicle model.

PHASE III RESULTS

Table 1 compares estimated and actual values of selected flight parameters as estimated by the first order regular perturbation solution and as obtained from numerical simulation of the dynamic equations with parameter values for *Slocum*.

ϵ	ϕ (°)		β (°)		θ (°)	V (m/s)	ω (rad/s)		R (m)	
	app.	actual	app.	actual	actual†	actual†	app.	actual	app.	actual
0.001	1.47	1.43	0.06	0.11	-8.7	0.77	0.003	0.003	253.33	256.67
0.005	7.37	7.11	0.23	0.57	-8.82	0.78	0.013	0.014	58.46	55.71
0.01	14.19	13.74	0.57	1.15	-8.9	0.79	0.03	0.03	29.73	30.37
0.03	42.59	34.84	1.72	4.01	-9.8	0.85	0.08	0.06	9.91	14.43
0.05	70.98	47.69	2.29	6.88	-9.87	0.91	0.13	0.07	5.95	13.22
0.07	99.37	55.84	3.44	8.59	-9.40	0.95	0.18	0.07	4.25	13.73

Table 1. Key turning flight parameters as estimated by a first order perturbation solution and obtained from numerical simulation of the dynamic equations. The vehicle parameters are those described in [Bhatta, 2006] for the* Slocum *glider.

[1] http://www.sandia.gov/isrc/UMBRA.html

For the given flight condition, the value of ε may be increased up to 0.0932, beyond which the simulation diverges. This value agrees with the eigenvalue locus shown in Figure 9. Note that one may infer stability of the true equilibrium from the eigenvalues of the linearization about the *approximate* equilibrium, provided the real part of every eigenvalue is sufficiently large negative compared with the magnitude of ε [Mahmoudian, Geisbert, & Woolsey, 2007].

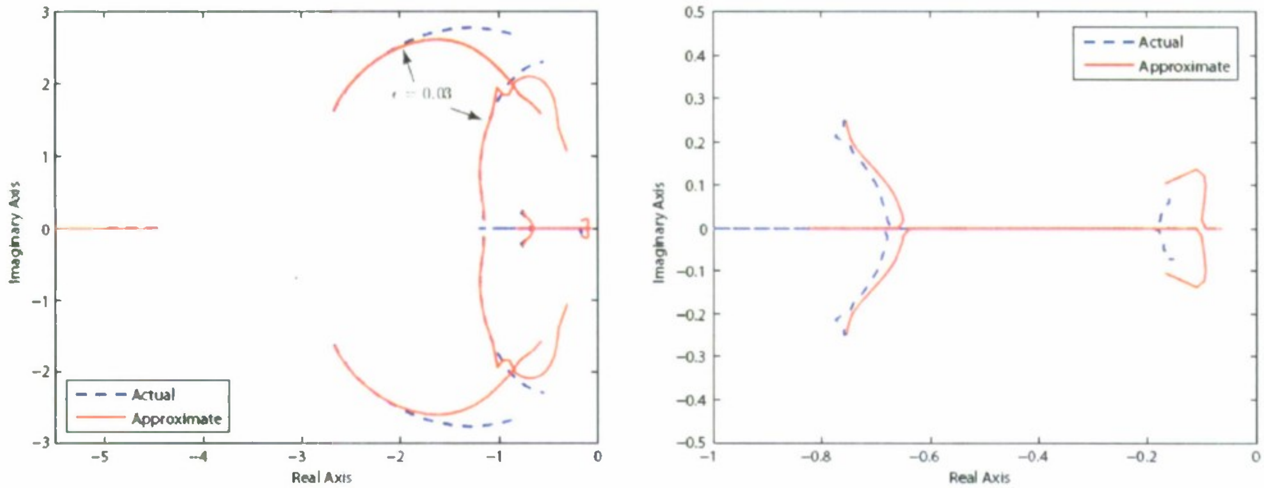

Figure 9. Eigenvalue loci for the system linearized about the actual and approximate equilibrium.

Having characterized steady wings level and turning flight, one can formulate a motion control strategy that relies on the analytical results. Given feasible values for desired speed, glide path angle, and turn rate, for example, one may compute "feedforward" actuator commands to adjust the net weight and center of gravity in order to achieve the given flight condition. A notional illustration of such a control system is shown in Figure 10.

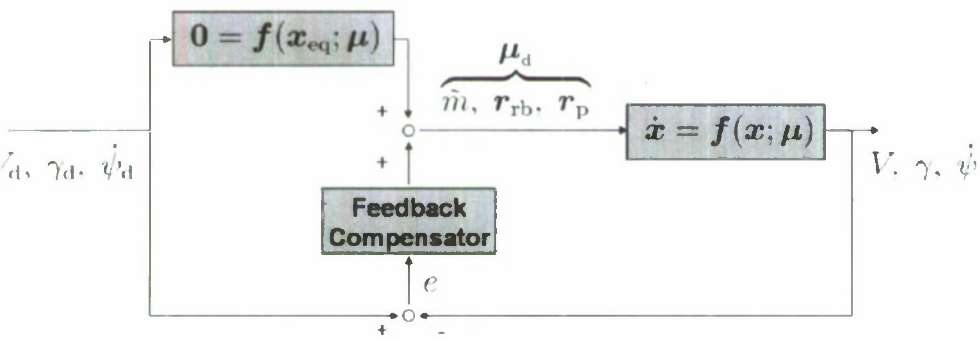

Figure 10. A steady motion based feedforward/feedback control system.

A logical next step is to develop a procedure for path planning which makes use of the preceding approximate results for equilibrium turning flight. A reasonable objective would be to concatenate these approximate equilibrium motions in order to minimize the time of transit, as predicted by the approximation, from a given initial point to a given final point with a specified initial and final heading. The question of reachability naturally arises, since an underwater glider must ascend or descend to locomote. A glider can not progress between two points at the same depth, for example, without concatenating at least one ascending and one descending motion. For the moment, we restrict

our attention to situations in which the final point is strictly below (above) the initial point and can be reached in a single descending (ascending) flight without exceeding the vehicle's physical limitations (such as the minimum glide slope). Actually, we will project the vehicle path onto the horizontal plane and simply ignore the vertical component of motion. A fortunate consequence of the structure of our approximate solution for turning flight is that, to first order, the horizontal and vertical components of velocity remain constant. Thus, the minimum time problem in the horizontal plane corresponds to minimizing the *change in depth* for a given horizontal point-to-point transition. Since an underwater glider propels itself by the force of gravity, minimizing the change in depth is equivalent to minimizing the energy expenditure.

Projecting the vehicle's motion onto the horizontal plane, glider equilibrium motions correspond to constant-speed straight-line and circular paths. The speed is determined solely by the vehicle net weight and, in practice, may be assumed to take the maximum achievable value. Considering only motion in the horizontal plane, one statement of the motion planning problem is the following: *choose the turn rate to minimize the time of transit from a given initial point to a given final point with a specified initial and final heading.*

Viewing the glider motion from directly above, the minimum time control problem is reminiscent of a planar vehicle which drives forward at constant speed and which may turn, in either direction, at any rate up to some maximum value. This type of control system has been studied quite thoroughly within the robotics and air vehicle communities beginning with a classic paper [Dubins, 1957] concerning time-optimal paths (or, equivalently, minimum length paths). The results are immediately applicable to optimal path planning for underwater gliders. Moreover, since gliders operate at or near their most efficient orientation (maximizing the ratio of lift to drag), time-optimal paths also minimize energy expended. Because time-optimal paths at constant speed minimize arclength, the net change in depth (and potential energy) is minimized.

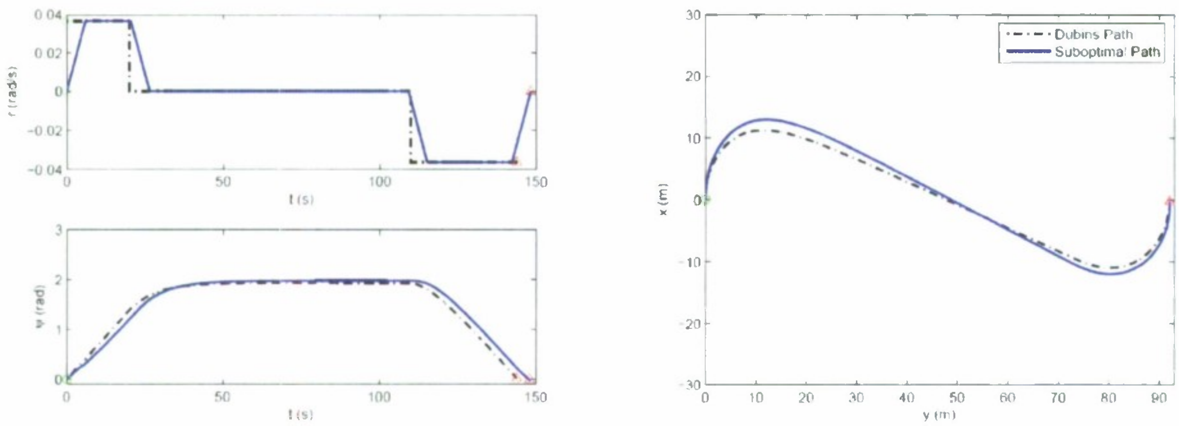

Figure 11. Dubins and suboptimal paths for the* Slocum *underwater glider, where either turn rate or turn acceleration serves as the input, respectively.

The classical Dubins car problem assumes that turn rate can be treated as an input with magnitude limits but no rate limits. The assumption may or may not be appropriate for wheeled robotic vehicles, but it is certainly not appropriate for underwater gliders. For these vehicles, turn rate is controlled indirectly by shifting the center of gravity to effect a banked turn. If instead we let turn *acceleration*

be the (bounded) input and impose a state constraint on the turn rate, then we obtain a suboptimal solution, as illustrated in Figure 11 for a particular maneuver.

PHASE III IMPACT/APPLICATIONS

To our knowledge, the first order approximate solution that we have obtained for steady turning flight of an underwater glider is the first of its kind. Having an explicit, analytical relationship between inertial parameters, stability derivatives, and steady turning flight conditions may inform future underwater glider designs, particularly with regard to lateral maneuverability. The analytical result also provides a foundation for parametric optimization of glide paths and transitions between glide paths, an improvement on the case-by-case numerical optimization that must be done in the absence of analytical solutions for steady turning motion.

Applications of buoyancy driven gliding extend beyond military and scientific applications in the earth's oceans. The technique may, for example, provide an extremely efficient method for exploring other worlds with dense atmospheres. One example that was explored in [Morrow, Woolsey, and Hagerman, 2006] involves mapping the surface of Titan, the heavily shrouded moon of Saturn, as illustrated in Figure 12.

Figure 12. Buoyancy driven gliders explore the surface of Titan. (Background by M. Messerotti. Used with permission.)

RELATED PROJECTS

Career: Internal Shape Control for Ocean and Atmospheric Vehicles
NSF Grant # CMS-0133210
PI: C. Woolsey
Status: Complete

Closely related to the ONR-sponsored effort, this project focuses on the development of basic theory for control of shape-controlled mechanical systems, from simple mechanical systems to ocean, atmospheric, and space vehicles. The project includes an educational component intended to cultivate excitement for learning and discovery among undergraduates through research experiences for undergraduates and engineering design competitions.

Heterogeneous Teams of Autonomous Vehicles: Advanced Sensing and Control
ONR Grant # N00014-05-1-0516
PI: C. Woolsey
Status: Complete

This project is a nine-investigator effort to develop theory and technology that will support autonomous coordination within heterogeneous teams of autonomous vehicles, including air, ground, and marine vehicles. The effort will develop mission-enabling sensor technology and fundamental theory for vehicle control and coordination. The resulting technology and algorithms will be demonstrated using a variety of new and existing autonomous vehicle platforms.

Adaptive Sampling in Dynamic Environments using AUVs
ONR Grant # N00014-05-1-0780
PI: D. Stilwell, Virginia Tech
Status: Complete

The principal objectives of this research project are to (1) develop and experimentally verify adaptive sampling algorithms for AUVs, (2) develop flow field identification algorithms to enable AUV navigation in highly dynamic environments, and (3) collaborate with Tulane and Xavier Universities in the packaging of a new class of biosensor for small AUVs.

Internally Actuated Lateral-Directional Maneuvering for a Blended Wing-Body Underwater Glider
ONR Grant # N00014-02-1-0588 (Continuation of existing grant.)
PI: C. Woolsey (Coordinated effort with Scripps Institute of Oceanography and UW/APL)
Status: Complete

This project focuses on the lateral-directional control challenges associated with low-speed, high angle of attack flight of an internally actuated, blended wing-body underwater glider. Specifically, this effort will develop and validate model-based steering control laws for the prototype blended wing-body glider being developed by the Scripps Institute of Oceanography's Marine Physical Laboratory and the University of Washington's Applied Physics Laboratory. The work is being pursued in coordination with investigators at those institutions.

Self-Sustaining Boundary-Layer-Adapted System for Terrain Exploration and Environmental Sampling
NIAC Grant # 07605-003-039
PI: C. Woolsey
Status: Complete

This project involved preliminary design of a system for remote terrain exploration and environmental sampling on worlds with dense atmospheres, such as Titan and Venus. The system consists of three

major components: a fleet of rechargeable, internally actuated, buoyancy-driven gliders which are programmed to soar at extremely low altitudes; a tethered, high-altitude, oscillating wing whose motion is tuned to extract maximum wind energy; and an attached, low-altitude docking station to inductively recharge the gliders, upload science data, and download revised mission commands.

Collaborative Research: A Two-stage Towing System For Swath-mapping Ocean Turbulence
NSF Grant # OCE-0220745
PI: A. Gargett, Old Dominion University
Status: Complete

This project involved design and construction of an actively stabilized towfish intended to house a five-beam acoustic Doppler current profiler. The intended application is detailed mapping of small-scale ocean turbulence.

REFERENCES

Bhatta, P., *Nonlinear Stability and Control of Gliding Vehicles*, PhD Dissertation, Princeton University, 2006.

Davis, R. E., C. C. Eriksen, and C. P. Jones, "Autonomous buoyancy-driven underwater gliders." In *Technology and Applications of Autonomous Underwater Vehicles*, Vo. 2. G. Griffiths, Ed. Taylor and Francis, 2002.

Davis, R. E., C. C. Eriksen, and C. P. Jones, "Autonomous buoyancy-driven underwater gliders." In Technology and Applications of Autonomous Underwater Vehicles, Vo. 2. G. Griffiths, Ed. Taylor and Francis, 2002.

Ericksen, C. C., T. J. Osse, R. D. Light, T. Wen, T. W. Lehman, P. L. Sabin, J. W. Ballard, and A M. Chiodi, "*Seaglider*: A long-range autonomous underwater vehicle for oceanographic research," *Journal of Oceanic Engineering, Special Issue on Autonomous Ocean Sampling Networks*, Vol 26, No. 4, pp. 424-436, 2001.

Graver, J. G., *Underwater Gliders: Dynamics, Control, and Design*, PhD Dissertation, Princeton University, 2005.

Graver, J. G., J. Liu, C. A. Woolsey, and N. E. Leonard, "Design and analysis of an underwater glider for controlled gliding," In Proc. *Conference on Information Sciences and Systems*, pp. 801-806, 1998.

Jenkins, S. A., D. E. Humphreys, J. Sherman, J. Osse, C. Jones, N. Leonard, J. Graver, R. Bachmayer, T. Clem, P. Carroll, P. Davis, J. Berry, P. Worley, and J. Wasyl, *Underwater Glider System Study*, ONR Technical Report, 2003.

Kim, H. Y. and C. A. Woolsey, "Directional control of an underwater vehicle by feedback passivation." *2004 American Control Conf.*, pp. 2998-3003, Boston, MA. July 2004.

Leonard, N. E., and J. G. Graver, "Model-based feedback control of autonomous underwater gliders," *Journal of Oceanic Engineering, Special Issue on Autonomous Ocean Sampling Networks*, Vol 26, No. 4, pp. 633-645, 2001.

N. Mahmoudian, J. Geisbert, and C. A. Woolsey, "Steady turns and optimal paths for underwater gliders." *AIAA Guidance, Navigation, and Control Conference*. (AIAA-2007-6602)

Morrow, M., "A Self-Sustaining, Boundary-Layer-Adapted System for Terrain Exploration and Environmental Sampling." M. S. Thesis, Virginia Polytechnic Institute and State University, June 2005.

Morrow, M., C. A. Woolsey, and G. Hagerman, "Exploring Titan with autonomous, buoyancy-driven gliders." *Journal of the British Interplanetary Society*, Vol. 59, No. 1, pp. 27-34, January 2006.

Nickell, C., "Modular Modification of a Buoyant AUV for Low-Speed Operation." M. S. Thesis, Virginia Polytechnic Institute and State University, September 2005.

Nickell, C., C. A. Woolsey, and D. J. Stilwell. "A low-speed control module for a streamlined AUV." *Proc. MTS/IEEE OCEANS 2005*, September 19-23, 2005, Washington, D. C.

Reddy, C. K., "Practical challenges in the method of controlled Lagrangians." Ph.D. Dissertation, Virginia Polytechnic Institute and State University, September 2005.

Reddy, C. K., and C. A. Woolsey, "Kinetic shaping for vehicles with moving mass actuators." *J. Vibration and Control.* [In review]

Reddy, C. K., W. Whitacre, and C. A. Woolsey, "Controlled Lagrangians with gyroscopic forcing: an experimental application." *2004 American Control Conf.*, pp. 511-516, Boston, MA. July 2004.

Schultz, C. and C. A. Woolsey, "An experimental platform for validating internal actuator control strategies." *IFAC Workshop on Guidance and Control of Underwater Vehicles*, pp. 209–214, Newport, South Wales, U.K. April 2003.

Sherman, J., R. E. Davis, W. B. Owens, and J. Valdes, "The autonomous underwater glider 'Spray'," *Journal of Oceanic Engineering, Special Issue on Autonomous Ocean Sampling Networks*, Vol 26, No. 4, pp. 437-446, 2001.

Stepanyan, V., N. Hovakimyan, and C. A. Woolsey. "Adaptive output feedback control of a spheroidal underactuated underwater vehicle." *Proc. MTS/IEEE OCEANS 2005*, September 19-23, 2005, Washington, D. C.

Webb, D. C. , P. J. Simonetti, and C. P. Jones, "*Slocum*: An underwater glider propelled by environmental energy," *Journal of Oceanic Engineering, Special Issue on Autonomous Ocean Sampling Networks*, Vol 26, No. 4, pp. 447-452, 2001.

Whitacre, W. W. "An autonomous underwater vehicle as a spacecraft attitude control simulator." *43rd AIAA Aerospace Sciences Meeting and Exhibit*. Reno, Nevada, January 10-13, 2005.

Woolsey, C. A., "Reduced Hamiltonian dynamics for a rigid body/mass particle system." *AIAA Journal of Guidance, Control, and Dynamics*. Vo. 28, No. 1, pp. 131-138, 2005.

Woolsey, C. A. "Directional control of a slender, underactuated AUV using potential shaping," *IEEE Conference on Decision and Control*, pp. 6826-6831, San Diego, CA, December 2006 (Invited paper.)
Woolsey, C. A. and L. Techy. "Cross-track control of a slender, underactuated AUV using potential shaping." *Ocean Engineering: Special Issue on AUVs* 36(1), pp. 82-91, January 2009.

Woolsey, C. A., C. K. Reddy, A. M. Bloch, D. E. Chang, N. E. Leonard, J. E. Marsden, "Controlled Lagrangian systems with gyroscopic forcing and dissipation." *European Journal of Control (Special Issue on Lagrangian and Hamiltonian Methods for Nonlinear Control)*. Vo. 10, No. 5, pp. 478-496, 2004.

Woolsey, C. A. and N. E. Leonard, "Stabilizing underwater vehicle motion using internal rotors." *Automatica*. Vo. 38, No. 12, pp. 2053—2062, 2002.

PUBLICATIONS

Note: Asterisks (*) denote undergraduate, graduate, or postdoctoral research assistants.

<u>Journal Papers</u>

Mahmoudian*, N., J. Geisbert*, and C. A. Woolsey. "Approximate analytical turning conditions for underwater gliders: Implications for motion control and path planning," *IEEE Journal of Oceanic Engineering* [Submitted, Refereed]

Techy*, L. and C. A. Woolsey "Minimum time path planning for UAVs in winds,". *AIAA Journal of Guidance, Control, and Dynamics* [Submitted, Refereed]

Woolsey, C. A. and L. Techy*. "Cross-track control of a slender, underactuated AUV using potential shaping." *Ocean Engineering: Special Issue on AUVs* 36(1), pp. 82-91, January 2009. [Published, Refereed]

Petrich*, J., C. A. Woolsey, and D. J. Stilwell. "Planar flow model identification for improved navigation of small AUVs." *Ocean Engineering: Special Issue on AUVs*. 36(1), pp. 119-131, January 2009. [Published, Refereed]

H.-Y. Kim* and C. A. Woolsey. "Global directional control of a slender AUV," *AIAA Journal of Guidance, Control, and Dynamics* 30(1), pp. 255-259, January-February 2007. [Published, Refereed]

Morrow*, M., C. A. Woolsey, and G. Hagerman. "Exploring Titan with autonomous, buoyancy-driven gliders." *Journal of the British Interplanetary Society*, 59(1), pp. 27-34, January 2006. [Published, Refereed]

Woolsey, C. A., "Reduced Hamiltonian dynamics for a rigid body/mass particle system." *AIAA Journal of Guidance, Control, and Dynamics*. Vo. 28, No. 1, pp. 131-138, 2005. [Published, Refereed]

Woolsey, C. A., C. K. Reddy*, A. M. Bloch, D. E. Chang, N. E. Leonard, J. E. Marsden, "Controlled Lagrangian systems with gyroscopic forcing and dissipation." *European Journal of Control (Special Issue on Lagrangian and Hamiltonian Methods for Nonlinear Control).* Vo. 10, No. 5, pp. 478-496, 2004. [Published, Refereed]

Chang, D. E., A. M. Bloch, N. E. Leonard, J. E. Marsden, and C. A. Woolsey, "The equivalence of controlled Lagrangian and controlled Hamiltonian systems for simple mechanical systems." *ESAIM: Control, Optimisation, and Calculus of Variations (Special Issue Dedicated to J. L. Lions).* Vo. 8, pp. 393–422, 2002. [Published, Refereed]

Woolsey, C. A. and N. E. Leonard, "Stabilizing underwater vehicle motion using internal rotors." *Automatica.* Vo. 38, No. 12, pp. 2053—2062. [Published, Refereed]

Conference Papers

Kraus*, R. J., C. A. Woolsey, and E. M. Cliff, "Optimal underwater glider trajectories in depth-varying currents," *Intl. Symp. on Unmanned Untethered Submersible Technology* [Accepted]

Mahmoudian*, N. and C. A. Woolsey. "Underwater glider path planning for efficient oceanographic sampling," *Intl. Symp. on Unmanned Untethered Submersible Technology* [Accepted]

Techy*, L., D. A. Paley, and C. A. Woolsey, "UAV coordination on convex curves in wind: An environmental sampling application," *2009 European Control Conference* [Accepted]

"Underwater glider motion control," N. Mahmoudian* and C. A. Woolsey, Proc. 47th IEEE Conference on Decision and Control, pp. 552 – 557, Cancun, Mexico, December 2008. [Published, Refereed]

Kraus*, R. J., E. M. Cliff, J. C. Luby, and C. A. Woolsey, "Optimal control for an underwater glider: Avoiding stall in a symmetric pull-up," *Proc. 18th International Symposium on Mathematical Theory of Networks and Systems*, Blacksburg, VA, August 2008 [Published, Refereed, Invited]

Mahmoudian*, N., J. Geisbert*, and C. A. Woolsey "Steady turns and optimal paths for underwater gliders," *AIAA Guidance, Navigation, and Control Conference.* (AIAA-2007-6602) [Published, Refereed]

Woolsey, C. A. "Directional control of a slender, underactuated AUV using potential shaping," *Proc. 45th IEEE Conference on Decision and Control*, pp. 6826-6831, San Diego, CA, December 2006 [Published, Refereed, Invited]

Reddy*, C. K. and C. A. Woolsey, "Energy shaping for vehicles with point mass actuators." *2006 American Control Conf.*, pp. 4291-4296, Minneapolis, MN. [Published, Refereed]

Petrich*, J., C. A. Woolsey, and D. J. Stilwell. "Identification of a low-complexity flow field model for AUV applications," *Proc. MTS/IEEE OCEANS 2005*, September 19-23, 2005, Washington, D. C. [Published]

Nickell*, C., C. A. Woolsey, and D. J. Stilwell. "A low-speed control module for a streamlined AUV." *Proc. MTS/IEEE OCEANS 2005*, September 19-23, 2005, Washington, D. C. [Published]

Stepanyan, V., N. Hovakimyan, and C. A. Woolsey. "Adaptive output feedback control of a spheroidal underactuated underwater vehicle." *Proc. MTS/IEEE OCEANS 2005*, September 19-23, 2005, Washington, D. C. [Published]

Kim*, H.-Y. and C. A. Woolsey, "Directional control of an underwater vehicle by feedback passivation." *2004 American Control Conf.*, pp. 2998-3003, Boston, MA. July 2004. [Published, Refereed]

Reddy*, C. K., W. Whitacre*, and C. A. Woolsey, "Controlled Lagrangians with gyroscopic forcing: An experimental application." *2004 American Control Conf.*, pp. 511-516, Boston, MA. July 2004. [Published, Refereed]

Schultz*, C. and C. A. Woolsey, "An experimental platform for validating internal actuator control strategies." *IFAC Workshop on Guidance and Control of Underwater Vehicles*, pp. 209–214, Newport, South Wales, U.K. April 2003. [Published, Refereed]

Woolsey, C. A. "Directional control of a slender, underactuated AUV using potential shaping," *IEEE Conference on Decision and Control*, pp. 6826-6831, San Diego, CA, December 2006 [Published, Refereed, Invited]

Woolsey, C. A. and A. E. Gargett, "Passive and active attitude stabilization for a tow-fish." *Proc. Conf. on Decision and Control*, pp. 2099–2104, Las Vegas, NV, December 2002. [Published, Refereed, Invited]

HONORS/AWARDS/PRIZES

2004 NASA Institute for Advanced Concepts (NIAC) Fellow

2002-2005 College of Engineering Faculty Fellow

2002 College of Engineering Dean's Award for Outstanding New Assistant Professor

2002-2007 NSF Faculty Early Career Development (CAREER) Award

2007 SAE Ralph R. Teetor Educational Award